4th International Conference on Contemporary Problems of Thermal Engineering
CPOTE 2016, 14-16 September 2016, Katowice, Poland
Institute of Thermal Technology

NEW GENERATION OF COMPUTER-AIDED TOOLS FOR EXERGETIC ANALYSIS OF THERMAL SYSTEMS

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Keywords: «cloud» tools, exergy analysis, Internet

Abstract

Exergy-based metholody provides new options for developing, evaluating and improving energy conversion systems. One of the main drawback associated with this approach is the necessity to conduct a large number of non-standard simulations (and the associated engineering time) that cannot always be easily provided by using commercially available software. Moreover, special software which enables to calculate thermodynamic properties of working fluids are needed for exergetic calculations. There are a wide range of such property packages but they have quite narrow opportunities for further application in computer simulations including exergetic ones.

In view of what is said above and taking into account that now different types of computers have a constant high speed connection to the Internet, a new technology for "cloud" exergetic computing of thermal systems is developed. The technology is based on Mathcad and Maple software and proposes three options for exergetic investigations: online calculation, download and reference.

Online resources provide exergetic calculations which can be manipulated interactively. As a result, every investigator and engineer has a web-access to the information and can run simulations with their own parameters without having to invest in new software. Downloading enables to download ready-made templates for further modified calculations on the own computer. The reference procedure gives a possibility to do a reference to the different exergy-based functions stored on the Internet or in "clouds" for developing further non-standard simulations. The tools were successfully tested using various case studies: advanced exergetic analysis of vapour compression cycle, Brayton cycle, and application of heating systems in building environment.

The proposed computational tools provide a possibility and flexibility to analyze, develop and share mathematical calculations and solutions in exergetic studies among different investigators, teams, located in different places, without having to do substantial investments in software.

1 Introduction

Exergy analysis is without a doubt a powerful tool for developing, evaluating and improving thermal systems. Due to exergy-based approach updated methodologies of design and operation of energy conversion processes is being developed. Advanced exergetic analysis, exergoeconomics (thermoeconomics), exergoenvironmental analysis - these new exergy approached methods are developed and applied to chemical industry, power sector, built environment, etc [1 - 4].

One of the main limitation associated with this approach especially applying the advanced exergy analyses is the necessity to conduct a large number of non-standard calculations and simulations (and the associated engineering time and effort) that cannot always be easily provided by using commercially available software [5], which has become widespread in the last three decades. The efforts of the improvements of the simulation programs are mostly based on the First Law of thermodynamics and classical economics. New methods (exergy-based approach, exergoeconomic and exergoenvironmental analyses, etc.) are seldom covered or even are not involved at all [6]. Moreover, application of exergy-based methodology requires data on thermodynamic properties of working fluids which are used in energy conversion and transfer processes. Today, for most cases of studies of thermal processes it is impractical, unrealistic and error-prone to use “paper” property tables or diagrams for thermodynamic values, enter them manually on a computer and conduct appropriate calculations or simulations. There are a wide range of such property packages (REFPROP, ChemCad, Thermo-Calc, etc.) but they have quite narrow opportunities for further application in computer simulations including exergetic ones. A wide variety of commercial software tools for the simulation of energy related processes have been developed and enhanced for different purposes (energy planning models, energy supply–demand models, forecasting models, renewable energy models, optimization models etc) based on different methods (e.g. AspenPlus, Pro/II, EES, Thermoflow, Gate Cycle, Ebsilon Professional, etc.) [7]. Most of these softwares are usually considered as “black box input-output” ones in the sense that there is no possibility to manipulate analytical expressions of the objective function or to observe the way in which those expressions are internally treated. Some of them can be applied to a very narrow area. In order to solve non-standard tasks researchers combine several types of programs. For example, in the work [6] the author exported the obtained results of simulations from existing software to a newly developed one for exergoeconomic analysis. In some cases such integration cannot be used directly and needs preprocessing. Moreover, such type of software can be used and reached by limited number of investigators.

New paradigm within information technologies - cloud computing has become a great solution for providing a flexible, instant, on-demand, cost saving and dynamically scalable computing infrastructure for many applications. Cloud computing presents a significant technology trend and many experts expect that it will substantially reshape information technology processes [8]. According to the NIST definition “Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction” [9].

The overall idea of the work is to develop open, interactive and web-based environment with reduced investments for application of exergetic analysis within thermal systems. The environment should provide data on thermophysical properties enabling easy integration with existing software, open and interactive algorithms and tools for exergetic studies, fast and universal access to exergetic calculations from a wide variety of devices, easy deploying exergy applications via Internet.

2 Methodology

It is proposed to develop the new generation of compuational tools on the basis of Mathcad and Maple and their interactive web-based publishers Mathcad Application/Calculation Server, PTC Mathcad Gateway and MapleNet.

Mathcad and its newest version Mathcad Prime are among of the most suitable softwares for engineering purposes, because they have three advantages: universality, accessibility, and cheapness. This package was originally designed as a package of numerical mathematics, which later was extended with symbolic kernel of the Maple. Maple is rather a symbolic computing and mathematical software package. It is very useful in the theoretical analysis. The latest version Maple 2016 provides data, computation and visualization tools for application with thermophysical properties of different working fluids which is especially valuable for exergetic calculations. Both Mathcad and Maple enable to solve a wide range of scientific, engineering, technical and training problems without using traditional programming.

Most today's software's developers propose web-based users' communities where it is possible to discuss projects, create documentation, share applications, ready-made templates, connect with peers and help others get the most out of the products – all these encourage collaboration and facilitate participation and interaction. Such users' communities exist within Mathcad and Maple softwares and are proposed to develop exergy-based computing.

Web-based product of Mathcad – Mathcad Application/Calculation Server was released at the end of 2003 and allows Mathcad users within an organization to deploy and distribute Mathcad worksheets. In January 19, 2016 Parametric Technology Corporation announced the release of PTC Mathcad Gateway solution [10]. This is developed as a Microsoft web service that provides interactive access to certified engineering calculations for any user, anytime, on any device.

MapleNet is a separate Maplesoft product that also provides a web-based learning platform for access to the Maple mathematical engine over the web [11]. MapleNet makes the computational power of Maple available regardless of the language or infrastructure used to create a web site, desktop applications, and mobile applications.

Mathcad environment has also a convenient tool: a reference to another Mathcad document, the variables and functions of which become accessible or, as programmers say, visible in the Mathcad document from which the corresponding reference is made. The Mathcad user doesn't need to open another calculation document and insert it in his/her calculation document: it is sufficient to make a reference to the appropriate file. After that, the user can use the functions programmed in the external document as if they have already been created in his/her document. Such reference can be made not only to Mathcad documents stored on a workstation or in a local area network, but also to documents available on websites. Owing to this circumstance, wide possibilities are opened for implementing a new technology of using functions available on websites without the need to download them on the user's computer [12].

A specific technology developed in [13] is applied within the work where a number of tools for the creation of the open and interactive algorithms were applied (see Figure 1). The algorithms 1 contain the following components: part 2 associated with the formulas for the calculation of parameters of a thermal system (thermophysical properties, performance characteristics, exergy-based parameters, etc.) and the corresponding Mathcad code 7; text part 3 that includes support information on formulas, notes to mathematical formulas and the description of the calculations, etc; part 4 related to computer and Internet technologies. The resource 1 provides a client with a number of options, including calculation of characteristics when manipulating data, reading of the text information and copying mathematical formulas or code in general. These options are executed on a remote server not on a personal computer of a user. The packages Mathcad Calculation Server 8 and Microsoft Expression Web 3 9 play an important role in the formation of the resource 1.

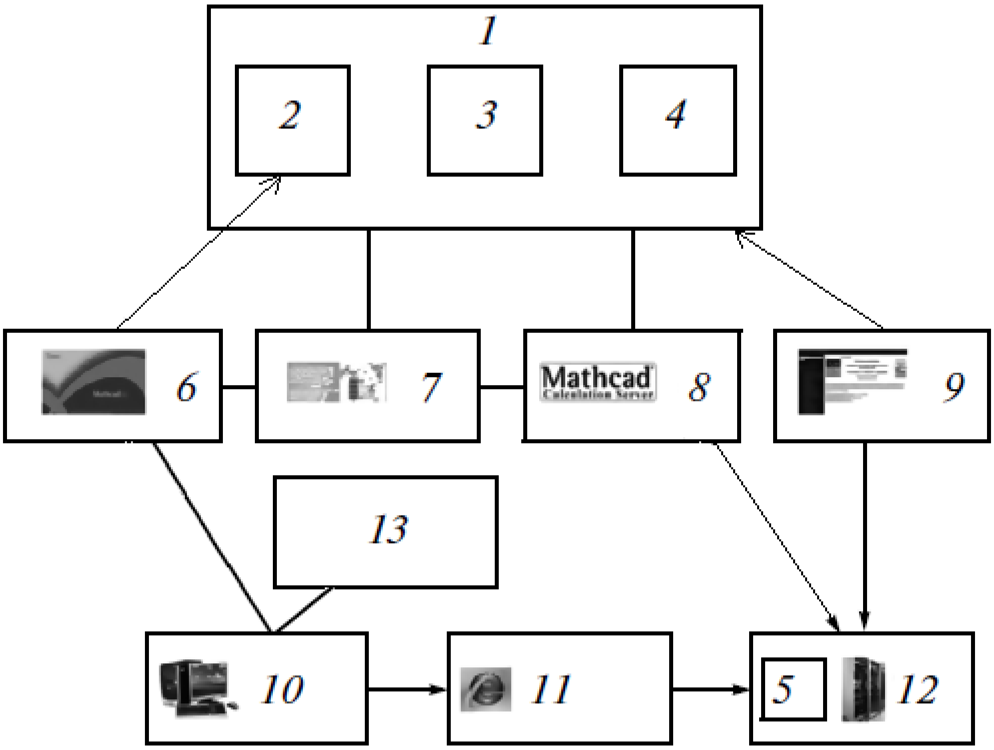


Figure 1: Sources of information and tools used to create an open interactive algorithm: the open interactive algorithm (1), Mathcad field of the algorithm (2), text (3), part associated with Computer Science and Internet technologies (4), the template (5), Mathcad-tools (6), Mathcad-program (7), Mathcad Calculation Server (8), package Microsoft Expression Web 3 (9), PC user (10), Internet (11), the remote server (12), the individual user program (13) [13]

3 Results

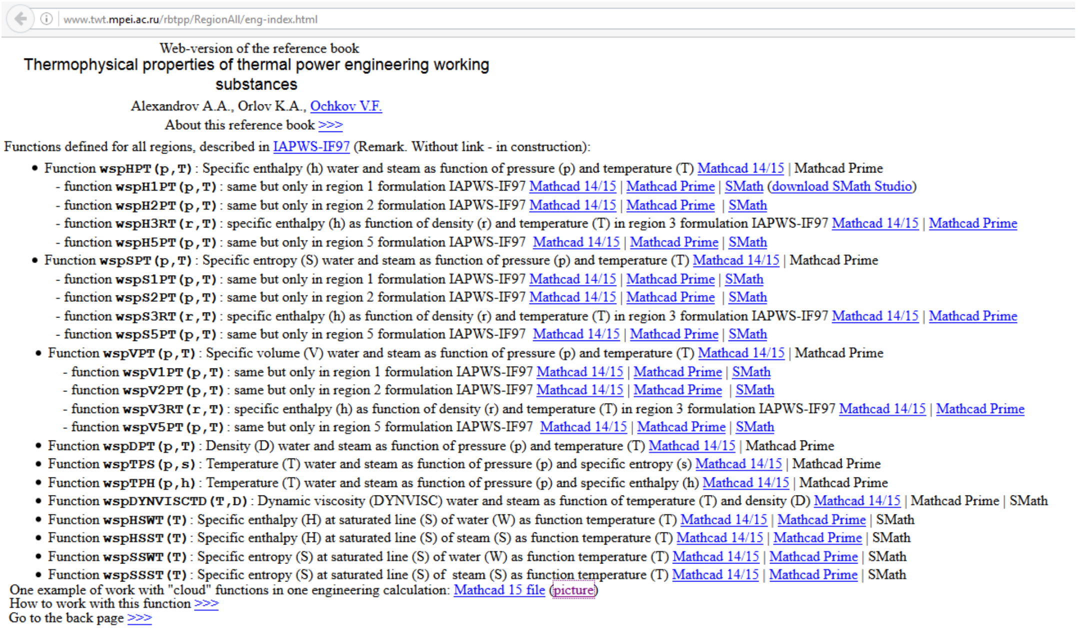
Figures 2, 3, 4 illustrate several but not all options with appropriate web-addresses for dealing with thermodynamic properties of working fluids: reference to “cloud” functions, downloading and on-line interactive calculations.

An example of input data block for interactive advanced exergetic analysis of simple Brayton cycle provided by technology of Mathcad Calculation Server is shown in Figure 5. The web-address of this calculation is also presented in Figure 5.

Figures 6 illustrates fragment of on-line web-based exergy analysis within built environment.

Mathcad’s user discussion forum of the authors’ book "Thermal Engineering studies with Excel, Mathcad and Internet" [17] is presented in Figure 7.

Screenshot of the web-page of the Maple application center offering free downloading a Maple document for advanced exergetic analysis of simple vapor compression refrigeration cycle is shown in Figure 8.



www.twt.mpei.ac.ru/rbtpp/RegionAll/eng-index.html

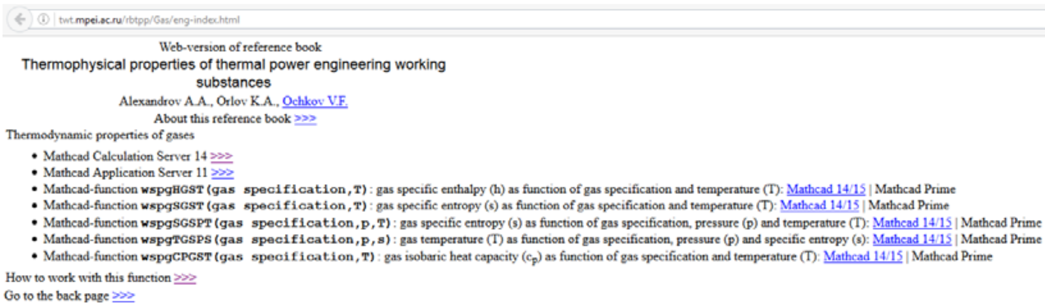
Web-version of the reference book
Thermophysical properties of thermal power engineering working substances
Alexandrov A.A., Orlov K.A., Ochkov V.F.
About this reference book >>>

Functions defined for all regions, described in IAPWS-IF97 (Remark. Without link - in construction):

- Function **wspHPT(p,T)**: Specific enthalpy (h) water and steam as function of pressure (p) and temperature (T) Mathcad 14/15 | Mathcad Prime
  - function **wspH1PT(p,T)**: same but only in region 1 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath (download SMath Studio)
  - function **wspH2PT(p,T)**: same but only in region 2 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath
  - function **wspH3RT(r,T)**: specific enthalpy (h) as function of density (r) and temperature (T) in region 3 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime
  - function **wspH5PT(p,T)**: same but only in region 5 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath
- Function **wspSPT(p,T)**: Specific entropy (S) water and steam as function of pressure (p) and temperature (T) Mathcad 14/15 | Mathcad Prime
  - function **wspS1PT(p,T)**: same but only in region 1 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath
  - function **wspS2PT(p,T)**: same but only in region 2 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath
  - function **wspS3RT(r,T)**: specific enthalpy (h) as function of density (r) and temperature (T) in region 3 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime
  - function **wspS5PT(p,T)**: same but only in region 5 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath
- Function **wspVPT(p,T)**: Specific volume (V) water and steam as function of pressure (p) and temperature (T) Mathcad 14/15 | Mathcad Prime
  - function **wspV1PT(p,T)**: same but only in region 1 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath
  - function **wspV2PT(p,T)**: same but only in region 2 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath
  - function **wspV3RT(r,T)**: specific enthalpy (h) as function of density (r) and temperature (T) in region 3 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime
  - function **wspV5PT(p,T)**: same but only in region 5 formulation IAPWS-IF97 Mathcad 14/15 | Mathcad Prime | SMath
- Function **wspDPT(p,T)**: Density (D) water and steam as function of pressure (p) and temperature (T) Mathcad 14/15 | Mathcad Prime
- Function **wspTPS(p,s)**: Temperature (T) water and steam as function of pressure (p) and specific entropy (s) Mathcad 14/15 | Mathcad Prime
- Function **wspTPH(p,h)**: Temperature (T) water and steam as function of pressure (p) and specific enthalpy (h) Mathcad 14/15 | Mathcad Prime
- Function **wspDYNVISCTD(T,D)**: Dynamic viscosity (DYNVISC) water and steam as function of temperature (T) and density (D) Mathcad 14/15 | Mathcad Prime | SMath
- Function **wspHSWT(T)**: Specific enthalpy (H) at saturated line (S) of water (W) as function temperature (T) Mathcad 14/15 | Mathcad Prime | SMath
- Function **wspHSST(T)**: Specific enthalpy (H) at saturated line (S) of steam (S) as function temperature (T) Mathcad 14/15 | Mathcad Prime | SMath
- Function **wspSSWT(T)**: Specific entropy (S) at saturated line (S) of water (W) as function temperature (T) Mathcad 14/15 | Mathcad Prime | SMath
- Function **wspSSST(T)**: Specific entropy (S) at saturated line (S) of steam (S) as function temperature (T) Mathcad 14/15 | Mathcad Prime | SMath

One example of work with "cloud" functions in one engineering calculation: Mathcad 15 file (picture)
How to work with this function >>>
Go to the back page >>>

Figure 2: Website with references to the functions on the thermodynamic properties of water and/or steam



twt.mpei.ac.ru/rbtpp/Gas/eng-index.html

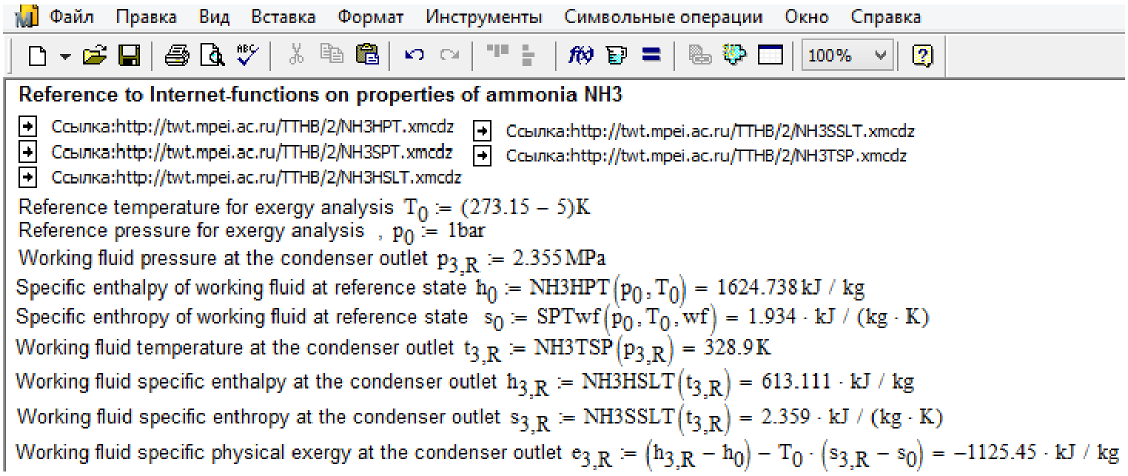
Web-version of reference book
Thermophysical properties of thermal power engineering working substances
Alexandrov A.A., Orlov K.A., Ochkov V.F.
About this reference book >>>

Thermodynamic properties of gases

- Mathcad Calculation Server 14 >>>
- Mathcad Application Server 11 >>>
- Mathcad-function **wspgHGST(gas specification,T)**: gas specific enthalpy (h) as function of gas specification and temperature (T): Mathcad 14/15 | Mathcad Prime
- Mathcad-function **wspgSGST(gas specification,T)**: gas specific entropy (s) as function of gas specification and temperature (T): Mathcad 14/15 | Mathcad Prime
- Mathcad-function **wspgSGSPT(gas specification,p,T)**: gas specific entropy (s) as function of gas specification, pressure (p) and temperature (T): Mathcad 14/15 | Mathcad Prime
- Mathcad-function **wspgTGSPS(gas specification,p,s)**: gas temperature (T) as function of gas specification, pressure (p) and specific entropy (s): Mathcad 14/15 | Mathcad Prime
- Mathcad-function **wspgCPGST(gas specification,T)**: gas isobaric heat capacity (c_p) as function of gas specification and temperature (T): Mathcad 14/15 | Mathcad Prime

How to work with this function >>>
Go to the back page >>>

Figure 3: Website with references to the functions on the thermodynamic properties of ideal gases and their mixtures



Файл Правка Вид Вставка Формат Инструменты Символьные операции Окно Справка

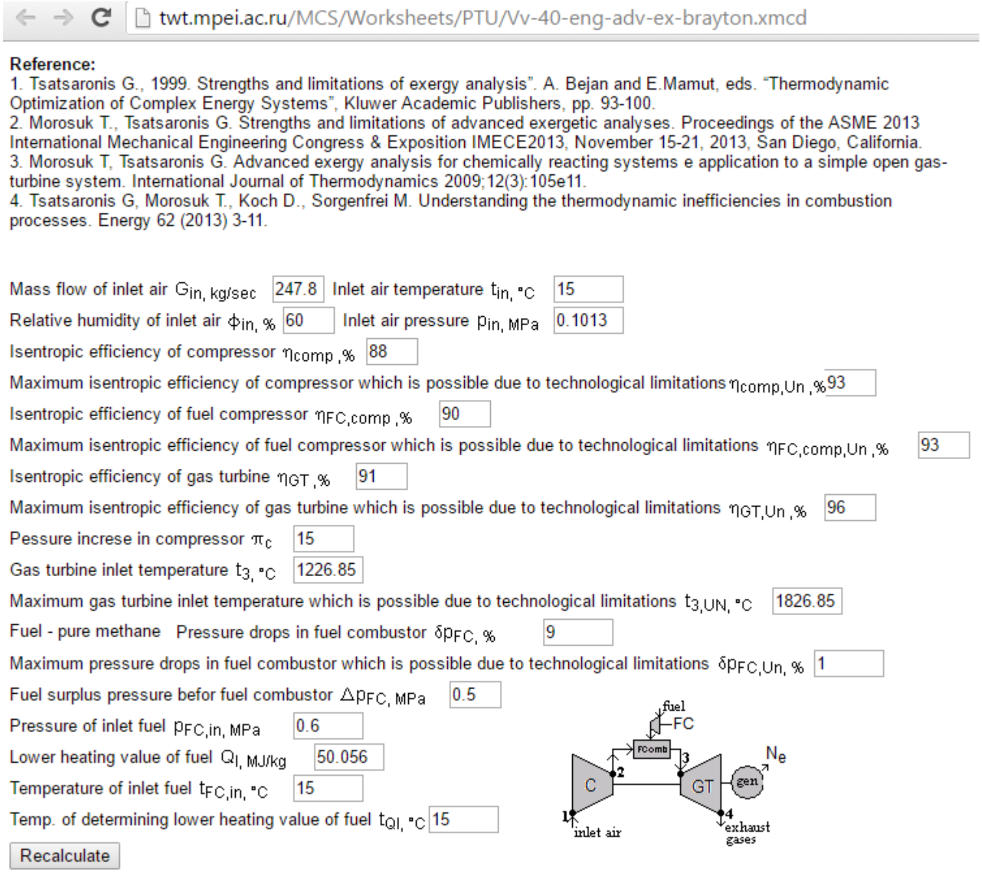
100%

Reference to Internet-functions on properties of ammonia NH3

Ссылка:http://twt.mpei.ac.ru/TTHB/2/NH3HPT.xmcdz
Ссылка:http://twt.mpei.ac.ru/TTHB/2/NH3SPT.xmcdz
Ссылка:http://twt.mpei.ac.ru/TTHB/2/NH3HSLT.xmcdz
Ссылка:http://twt.mpei.ac.ru/TTHB/2/NH3SSLT.xmcdz
Ссылка:http://twt.mpei.ac.ru/TTHB/2/NH3TSP.xmcdz

Reference temperature for exergy analysis $T_0 := (273.15 - 5)K$
Reference pressure for exergy analysis , $p_0 := 1bar$
Working fluid pressure at the condenser outlet $p_{3\_R} := 2.355MPa$
Specific enthalpy of working fluid at reference state $h_0 := NH3HPT(p_0, T_0) = 1624.738 kJ / kg$
Specific enthropy of working fluid at reference state $s_0 := SPTwf(p_0, T_0, wf) = 1.934 \cdot kJ / (kg \cdot K)$
Working fluid temperature at the condenser outlet $t_{3\_R} := NH3TSP(p_{3\_R}) = 328.9K$
Working fluid specific enthalpy at the condenser outlet $h_{3\_R} := NH3HSLT(t_{3\_R}) = 613.111 \cdot kJ / kg$
Working fluid specific enthropy at the condenser outlet $s_{3\_R} := NH3SSLT(t_{3\_R}) = 2.359 \cdot kJ / (kg \cdot K)$
Working fluid specific physical exergy at the condenser outlet $e_{3\_R} := (h_{3\_R} - h_0) - T_0 \cdot (s_{3\_R} - s_0) = -1125.45 \cdot kJ / kg$

Figure 4: An example of reference to “cloud” functions for calculations of thermodynamic properties of ammonia performed within user’s Mathcad worksheet


twt.mpei.ac.ru/MCS/Worksheets/PTU/Vv-40-eng-adv-ex-brayton.xmcd

Reference:
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4. Tsatsaronis G, Morosuk T., Koch D., Sorgenfrei M. Understanding the thermodynamic inefficiencies in combustion processes. Energy 62 (2013) 3-11.

Mass flow of inlet air $G_{in,\ kg/sec}$ 247.8 Inlet air temperature $t_{in,\ °C}$ 15
Relative humidity of inlet air $\phi_{in,\ \%}$ 60 Inlet air pressure $p_{in,\ MPa}$ 0.1013
Isentropic efficiency of compressor $\eta_{comp,\%}$ 88
Maximum isentropic efficiency of compressor which is possible due to technological limitations $\eta_{comp,Un,\%}$ 93
Isentropic efficiency of fuel compressor $\eta_{FC,comp,\%}$ 90
Maximum isentropic efficiency of fuel compressor which is possible due to technological limitations $\eta_{FC,comp,Un,\%}$ 93
Isentropic efficiency of gas turbine $\eta_{GT,\%}$ 91
Maximum isentropic efficiency of gas turbine which is possible due to technological limitations $\eta_{GT,Un,\%}$ 96
Pessure increse in compressor π_c 15
Gas turbine inlet temperature $t_{3,\ °C}$ 1226.85
Maximum gas turbine inlet temperature which is possible due to technological limitations $t_{3,UN,\ °C}$ 1826.85
Fuel - pure methane Pressure drops in fuel combustor $\delta p_{FC,\ \%}$ 9
Maximum pressure drops in fuel combustor which is possible due to technological limitations $\delta p_{FC,Un,\ \%}$ 1
Fuel surplus pressure befor fuel combustor $\Delta p_{FC,\ MPa}$ 0.5
Pressure of inlet fuel $p_{FC,in,\ MPa}$ 0.6
Lower heating value of fuel $Q_{l,\ MJ/kg}$ 50.056
Temperature of inlet fuel $t_{FC,in,\ °C}$ 15
Temp. of determining lower heating value of fuel $t_{Ql,\ °C}$ 15
Recalculate

Figure 5: Input data block for "cloud" advanced exergy analysis of simple Brayton cycle provided by technology of Mathcad Calculation Server

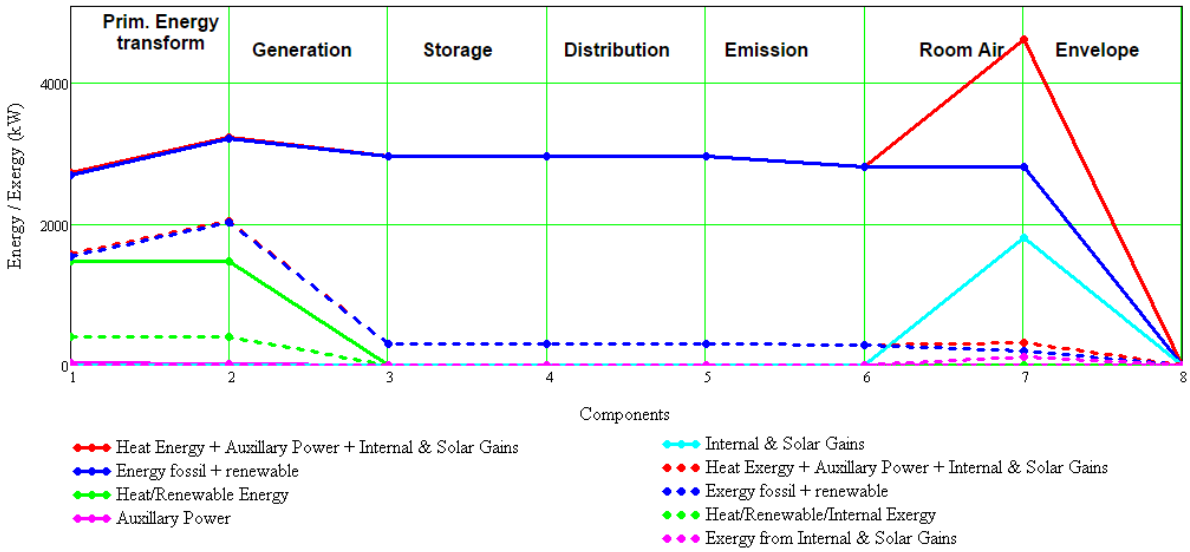

Figure 6: Exergy and energy flows through components for space heating supply performed within the open web-based resource

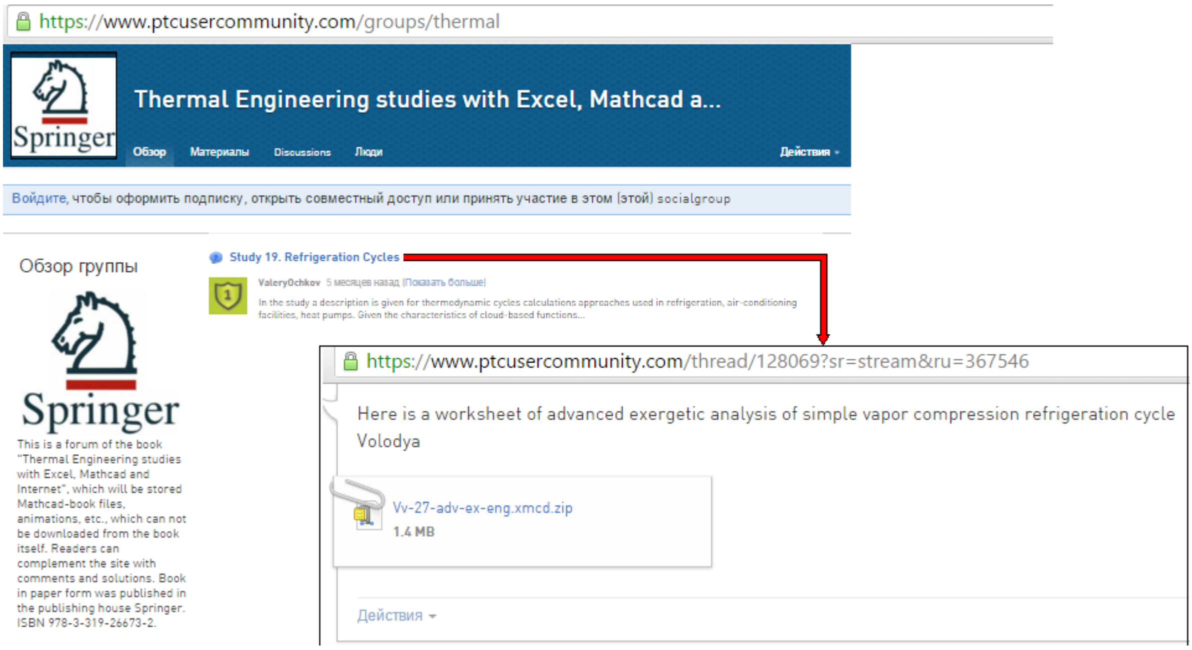

Figure 7: Screen shot of the web-page of PTC community where a Mathcad document for advanced exergetic analysis of simple vapor compression refrigeration cycle is proposed for downloading

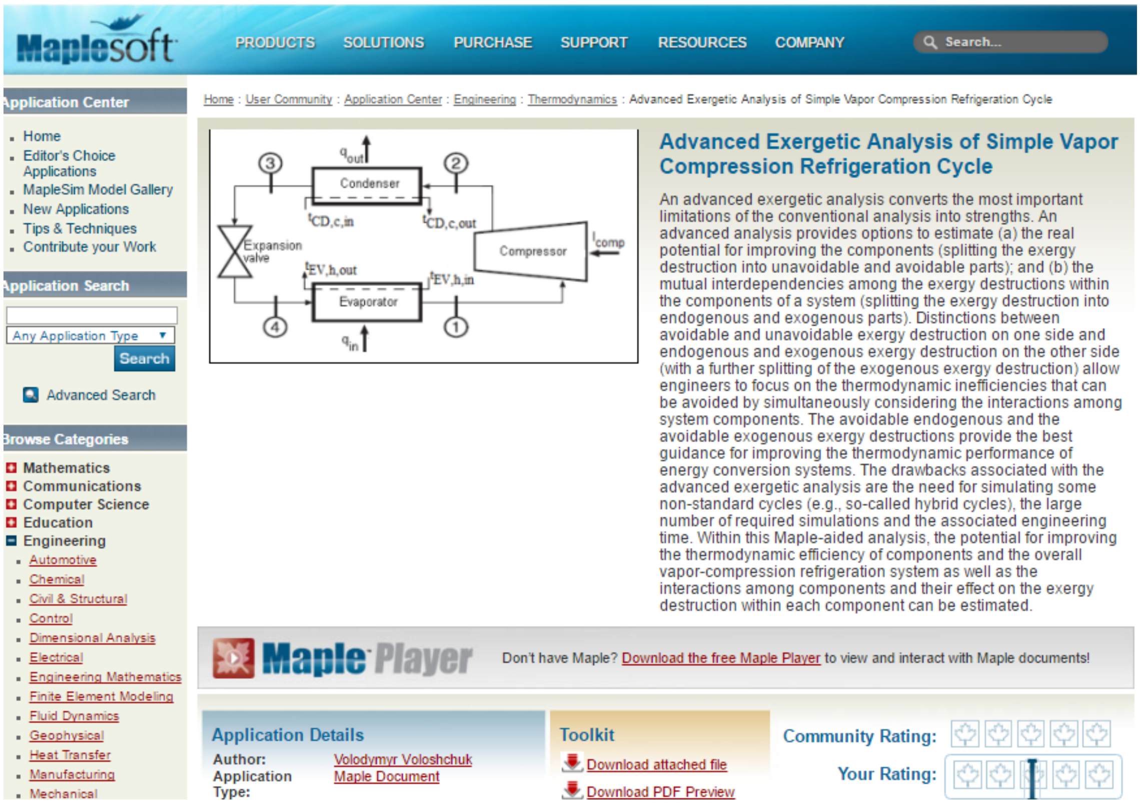

Figure 8: Screen shot of the web-page of the Maple application center where a Maple document for advanced exergetic analysis of simple vapor compression refrigeration cycle is proposed for downloading

4 Discussion

Based on the technology from [13] a wide range of network, open and interactive functions on thermophysical properties of working fluids applied in thermal systems were developed and located at http://twt.mpei.ac.ru/OCHKOV/VPU_Book_New/mas/eng/index.html (see Figures 2, 3). Such data on the thermophysical properties of water and steam, substances used as the main working fluid in thermal engineering, are programmed according to the formulations of Association for the Properties of Water and Steam approved in 1997 and refined in 2007 [14, 15]. The fuctions on properties of ideal gases and their mixtures are provided based on system of equations from [16]. In [17] the authors have proposed a methodology for creation of forward and backward functions that return the values of the thermophysical properties of refrigerants on the basis of tabular values in different areas of the state: single-phase region, two phase region, the saturation line. The tabulated data were generated in the NIST program REFPROP (http://www.nist.gov).
It is not only possible to download and place the functions located in the server http://twt.mpei.ac.ru/OCHKOV/VPU_Book_New/mas/eng/index.html into user's worksheet but also to do Internet-reference to the functions and to perform on-line calculations manipulating initial data. This is provided within the technology of Mathcad Calculation Server which supports all built-in math functionality offered in Mathcad.

Figure 4 illustrates calculations of specific physical exergy of ammonia at a condenser outlet in a refrigeration system performed in Mathcad software. For this case values of such thermodynamic properties as specific enthalpy, entropy, and temperature calculated for the reference and specified (condenser outlet) states respectively are needed. The reference to "cloud" functions for computing these properties is performed. For this purpose a user should enter the server http://twt.mpei.ac.ru/OCHKOV/VPU_Book_New/mas/eng/index.html and using navigation system find appropriate functions of interested working fluid (in the case analyzed – ammonia). Then one should click on the chosen function by the right hand mouse button. After this in the popup menu, it is necessary to choose "Properties", highlight and copy the corresponding URL address. Finally, turning to the Mathcad document and choosing the menu items "Insert" and then "Reference" a user can insert the previously copied address in the appeared window. After such reference the necessary functions will become available (visible, as programmers say) in the user's Mathcad worksheet, which enables calculating the necessary properties of the ammonia, depending on the specified parameters (see Figure 4).

On-line option of the server http://twt.mpei.ac.ru/OCHKOV/VPU_Book_New/mas/eng/index.html provides a possibility to perform interactive exergetic investigations of different thermal systems.

Figure 5 shows a web-based set of initial parameters located in special "live" cells which can be manipulated in an interactive mode for advanced exergetic analysis of simple Brayton cycle. After filling in input data and pressing the button "Recalculate" an investigator, engineer, etc. can receive both intermediate and final results of computing (numerical, analytical, graphical) similarly as in case of using Mathcad options.

Another application of web-based interactive tool is demonstrated on example of exergetic investigation of built environment (see Figure 6). The methodology of calculation is based on the one developed in [18]. A set of data concerning outdoor climatic parameters, building performance as well as heating ventilation and air conditioning systems characteristics can be entered and selected directly by the user on the provided web-page. The results of calculations are presented in numerical, analytical and graphical manner. As in previous case it is possible to analyze all steps of numerical investigations within the energy chain – from the primary energy source to the building and the environment.

As a result of development of on-line, interactive tools and algorithms for thermal calculations the authors have published a book “Thermal Engineering Studies with Excel, Mathcad and Internet“ [17]. The work provides the fundamentals of the application of mathematical methods, modern computational tools (Excel, Mathcad, SMath, etc.) and Internet to solve the a wide variety problems of heat and mass transfer, thermodynamics, fluid dynamics, energy conservation and energy efficiency. All calculation methods are provided with links to online computational pages. The book is complemented with a forum on PTC community where it is possible to download Mathcad- files, comment and propose own solutions (see Figure 7 for the case of advanced exergetic analysis of simple vapor compression refrigeration cycle).

Maple is another software which also provides cloud computing services. Including data about thermophysical properties of working fluids in the latest version Maple 2016 enables to perform thermal calculations in Maple without referring to external programs. A set of Maple documents for thermal calculations are prepared by the authors and uploaded to the Maplesoft user community for reviewing, discussing and sharing. Figure 8 presents one of such document for advanced exergetic analysis of simple vapor compression refrigeration cycle. In this document functions on thermodynamic properties of different working fluids were fruitfully used. Next phase of implementation of these Maple-based computing is online web-based applications using the technology of MapleNet.

Conclusions

New tendencies in computer-aided engineering based on “cloud” technologies enable to develop web-based generation of computing tools applied to exergetic analysis of thermal systems.

The mathematical package Mathcad with Mathcad Calculation Server (Mathcad Net Publisher) allowed to develop a “cloud” server http://twt.mpei.ac.ru/ochkov/VPU_Book_New/mas/eng/index.html for engineers and scientists, who perform computer simulations and modeling of thermal systems, including exergetic ones. The server considers online, reference and downloads solutions over a web-interface using the Mathcad software that runs remotely within the “cloud”. It results in fast access to data on thermophysical properties which can be easily integrated with personal Mathcad environment. It also provides web-based interactive algorithms and methodologies for on-line exergetic analysis of thermal systems.

PTC Mathcad Gateway is further solution for universal access to engineering calculations where it is possible to provide exergetic studies and which will be developed in the next step of the work.

PTC Mathcad community provides solutions for solving, analyzing, and sharing vital engineering calculations, including exergetic ones.

Including data about thermophysical properties of working fluids in the latest version Maple 2016 also enables to create ready-made templates for exergetic calculations. Through the Maple Application Center it is possible to distribute them among Maple users. Deploying Maple-based exergetic computing throughout the Internet with the help of the technology of MapleNet is another step of online applications.

The proposed technologies can substantially save time and money of engineers and investigators applying exergy-based methods.

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